# Influence of volcanic eruptions on the climate of the Asian monsoon region

K. J. Anchukaitis,[1] B. M. Buckley,[1] E. R. Cook,[1] B. I. Cook,[1,2] R. D. D'Arrigo,[1] and C. M. Ammann[3]

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[1] Several state-of-the-art general circulation models (GCMs) predict that large volcanic eruptions should result in anomalous dry conditions throughout much of monsoon Asia. Here, we use long and well-validated proxy reconstructions of Asian droughts and pluvials to detect the influence of volcanic radiative forcing on the hydroclimate of the region since the late Medieval period. Superposed epoch analysis reveals significantly wetter conditions over mainland southeast Asia in the year of an eruption, with drier conditions in central Asia. Our proxy and model comparison suggests that GCMs may not yet capture all of the important ocean-atmosphere dynamics responsible for the influence of explosive volcanism on the climate of Asia. **Citation:** Anchukaitis, K. J., B. M. Buckley, E. R. Cook, B. I. Cook, R. D. D'Arrigo, and C. M. Ammann (2010), Influence of volcanic eruptions on the climate of the Asian monsoon region, *Geophys. Res. Lett.*, *37*, L22703, doi:10.1029/2010GL044843.

## 1. Introduction

[2] Volcanic eruptions are an important climate forcing mechanism at seasonal to multidecadal timescales [*Shindell et al.*, 2004; *Gleckler et al.*, 2006; *Emile-Geay et al.*, 2008], and the global mean temperature response to the associated radiative forcing has been used as one constraint on climate system sensitivity and feedbacks [e.g., *Annan and Hargreaves*, 2006]. Long, annually-resolved historical and paleoclimate reconstructions have also enabled evaluation of substantially more eruptions [*Adams et al.*, 2003; *Fischer et al.*, 2007; *D'Arrigo et al.*, 2008] and reveal distinct seasonal spatiotemporal fingerprints in the response of surface temperatures to these eruptions that can be directly compared to forced general circulation model (GCM) simulations [e.g., *Shindell et al.*, 2004].

[3] Tree rings have previously been used to detect the timing and influence of volcanic eruptions on regional temperatures prior to instrumental observations [e.g., *LaMarche and Hirschboeck*, 1984]. *Fischer et al.* [2007] also examined the influence of large, well-dated tropical eruptions on European precipitation and *Adams et al.* [2003] detected the influence of volcanic events on tropical Pacific sea surface temperatures. *D'Arrigo et al.* [2008] used multiple proxies to examine the tropical temperature response to high and low latitude volcanism over the last 400 years. However, there has thus far been no comprehensive attempt to determine the long-term response of the Asian monsoon system to volcanic forcing, probably because suitable exactly-dated high-resolution proxy records of monsoon region hydroclimate have been sparse or unavailable. Several GCM simulations [*Oman et al.*, 2005; *Schneider et al.*, 2009; *Fan et al.*, 2009] predict drought conditions over monsoon Asia in response to large tropical and extratropical eruptions, and *Trenberth and Dai* [2007] observed dry conditions in the region following the eruption of Pinutubo in 1991, although this year also corresponded to a persistent El Niño. Here, we use new tree-ring-based proxy drought reconstructions to examine the influence of major volcanic eruptions on the climate of Asia and to evaluate the ability of GCMs to capture the actual temporal and spatial response of the monsoon system.

## 2. Materials and Methods

[4] We used Superposed Epoch Analysis (SEA) [*Haurwitz and Brier*, 1981] to evaluate the influence of explosive volcanic eruptions on the hydroclimate of the Asian monsoon region on two long tree ring-based proxy moisture reconstructions from the region that cover the period from the later half of the Medieval Climate Anomaly to the present. The first is from a tree-ring chronology from the long-lived cypress species *Fokienia hodgsonii* from Bidoup Nui Ba National Park (BNDP) in the highlands of southern Vietnam [*Buckley et al.*, 2010]. This chronology has a robust association with early monsoon season rainfall and extends back to the late Medieval epoch (1250 to 2008 CE), making it exceptional among tropical tree ring chronologies. The second dataset is the 'Monsoon Asia Drought Atlas' (MADA) [*Cook et al.*, 2010], a gridded ensemble spatiotemporal reconstruction of the boreal summer (JJA) Palmer Drought Severity Index (PDSI) extending from 1000 to 1989 CE (back to 1250 CE with sufficient sample depth over the spatial domain), which includes the BDNP among its 327 tree-ring proxy records. These records provide well-replicated, well-validated paleoclimate data that allow us evaluate the spatial and temporal hydroclimatic response to volcanic eruptions over the last eight centuries.

[5] In order to compare these two drought records to climate model predictions, we also derived [cf. *Touchan et al.*, 2010] PDSI values from the monthly temperature and precipitation output from the forced millennial climate model simulation using the NCAR CSM 1.4 [*Ammann et al.*, 2007].

[1]Lamont-Doherty Earth Observatory, The Earth Institute at Columbia University, Palisades, New York, USA.
[2]NASA Goddard Institute for Space Studies, New York, New York, USA.
[3]Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, USA.


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**Table 1.** Event years used in this study[a]

| Source | Event Years (CE) |
|---|---|
| *Ammann et al.* [2007] | 1258, 1259, 1269, 1278, 1279, 1452, 1453, 1600, 1601, 1641, 1809, 1810, 1815, 1816, 1884, **1903** |
| *Ammann and Naveau* [2003] | 1443, 1452, 1459, 1463, 1490, 1504, 1512, 1522, 1554, 1568, 1571, **1586**, 1595, 1600, 1605, **1619**, 1622, 1641, **1660**, 1665, 1674, 1680, 1693, 1712, 1721, 1728, **1737**, 1744, 1749, 1752, 1760, 1774, 1789, 1794, 1808, 1813, 1815, 1823, 1831, 1835, 1861, 1880, 1883, **1890**, **1902**, **1903**, 1911, 1928, 1953, *1963*, 1968, 1974, *1982* |
| *Fischer et al.* [2007] | **1586**, 1596, 1600, 1641, 1673, 1809, 1815, 1823, 1831, 1835, 1883, **1903**, *1963*, *1982* |

[a]While the range of all possible years is 1250 to 1989 CE, *Ammann and Naveau* [2003] and *Fischer et al.* [2007] considered only the period since 1400 and 1500 CE, respectively. Events years that occur at known or near reconstructed El Niño years are shown in bold following *Gergis and Fowler* [2006] and italics following *Trenberth and Dai* [2007].

The model simulates the period 850 to 1999 CE and uses an annual volcanic forcing series derived from ice core sulfate records. The common period of overlap between our proxy and model data is therefore 1250 to 1989 CE.

[6] We assembled three possible sets of events years during this period from the existing literature (Table 1). These were selected so as to be most comparable to other existing simulations or model/data comparisons, and to cover a range of tropical-to-extratropical as well as weak to strong events. First, we used the same volcanic forcing data applied by *Ammann et al.* [2007] for the millennium forced climate simulation using CSM1.4. From the annual forcing series we selected those years in which changes in the optical depth following eruptions resulted in an estimated radiative forcing of at least −1.7 W/m$^2$, equivalent to the eruption of Santa Maria in Guatemala in 1903 CE. For reference, in this dataset the 1258 CE eruption has a maximum radiative forcing of nearly −12 W/m$^2$ while Pinatubo is associated with a forcing of −1.37 W/m$^2$. Second, we considered all eruption years since 1400 CE as identified by *Ammann and Naveau* [2003], for a total of 53 events. Finally, we assembled a set of 14 eruption years since 1500 CE based on the large tropical eruptions selected by *Fischer et al.* [2007]. *Fischer et al.* [2007] made partial use of *Ammann and Naveau* [2003] in defining their event years, although only the largest and well-dated events were included. We adjusted the 'Year 0' from *Fischer et al.* [2007] where necessary to reflect the JJA monsoon season and the MADA reconstruction. We note that thus composed, the event lists include at least two significant tropical eruptions that are known to have been accompanied by El Niño events [*Trenberth and Dai*, 2007] in 1963 and 1982. Other El Niño events could also coincide with prehistoric eruptions (see Table 1).

[7] We use two methods to test the statistical significance of the temporal relationships between Asian monsoon drought and volcanic eruptions detected using SEA. First, we use a conventional bootstrapped resampling with replacement [*Haurwitz and Brier*, 1981] where confidence intervals are calculated by repeating the SEA using repeated (n = 10,000) random draws of pseudo-'event' years from the available time span. Significance is then evaluated by comparing percentiles from the random draw to the composite mean of the real data. A second approach follows *Adams et al.* [2003] and was applied to analysis of the BDNP chronology. It uses a randomized block reordering on the data SEA matrix itself. This method seeks to account for the autocorrelation structure of the proxy or climate data, although it can be sensitive to the total size of the epochal window. Following *Adams et al.* [2003], we normalized the data in the event windows to avoid the possibility that any single eruption would dominate the epochal signal. This was accomplished by dividing the values in each event window by the magnitude of the largest value in that window.

## 3. Results

[8] The superposed epoch analysis on the BDNP chronology shows statistically significant pluvial conditions in the event year (Year 0) for all three eruption lists (Figure 1). The same result is found irrespective of the method used to evaluate statistical significance. The SEA using the event years from *Ammann et al.* [2007] is smoother, showing a progressive transition from wetter conditions in southeast Asia in the event year and adjacent years to dry but non-significant values. This smooth transition and the apparent significant wet anomalies in Year-1 reflect consecutive 'event' years (e.g 1258 and 1259, 1452 and 1453) where the volcanic radiative forcing remained below −1.7 W/$m^2$ after the eruption. While all event lists suggest somewhat drier conditions in mainland southeast Asia ranging between 1 to 5 years following an eruption, only in the case of Year+2 from the *Fischer et al.* [2007] list is it found to be significantly drier at the 90% significance (one-tailed) level (see also Figure S1 of the auxiliary material).[1]

[9] The MADA shows wetter conditions over southeast Asia and drier conditions over the extra-tropical part of the domain in central Asia (Figure 2). This southeast Asia pattern appears to be relatively stable in time, while central Asia drying is pronounced since the early 18th century (see Figure S2 of the auxiliary material). A greater fraction of the domain-wide anomalies are found to be significant at the 90% confidence interval for the event lists composed of the strongest eruptions from *Ammann et al.* [2007]. For the larger set of 54 eruptions [*Ammann and Naveau*, 2003], only portions of Mongolia and southeast Asia show coherent significant anomaly patterns. No overall coherent pattern is detected in the data in eastern China. SEA on the derived PDSI from the millennium CSM 1.4 simulation (Figure 3) shows wetter conditions over western China and drier conditions in southeast Asia and much of eastern China, although for the strongest eruptions the CSM1.4 and

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL044843.

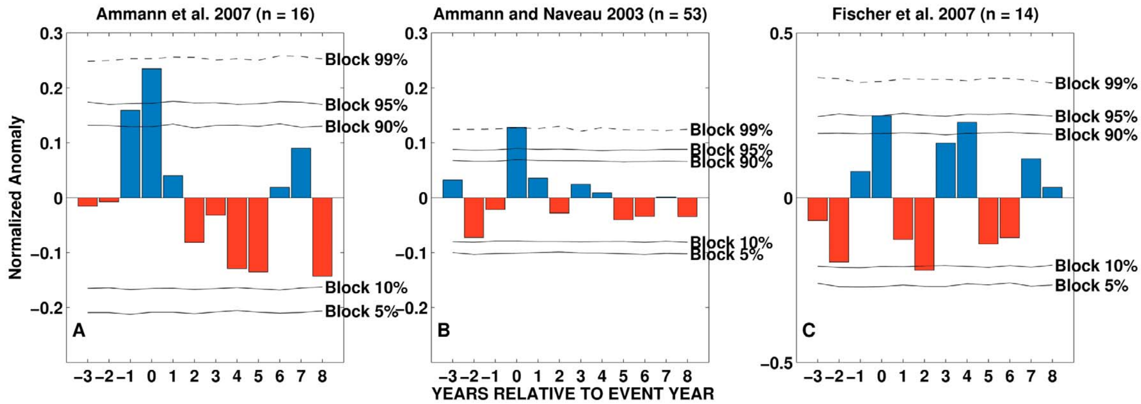


**Figure 1.** Superposed epoch analysis using the Bidoup Nui Ba tree-ring chronology and the three sets of events years shown in Table 1. Significance levels derived from Monte Carlo block resampling (n = 10,000) of the actual event year windows [*Adams et al.*, 2003] are indicated by horizontal lines in the plot. The 12 year window was selected to allow for 3 full independent blocks per event per resampling. Values in each event window were normalized by the largest magnitude excursion in that window to avoid a single eruption leveraging the mean epochal anomalies [cf. *Adams et al.*, 2003]. Wet anomalies in Year+4 in the *Fischer et al.* [2007] event list reflect the influence of the 4 year spacing of 4 of the 14 eruptions (1596 and 1600 CE, 1831 and 1835 CE).

MADA data agree over part of this latter region. Particularly in the model, the sign of the anomalies over India and Mongolia depend on the particular set of event years considered.

## 4. Discussion

[10] Several climate models predict strongly anomalous dry conditions over southeast Asia and wetter conditions over central Asia, (Figure 3 and *Fan et al.* [2009]; *Schneider et al.* [2009]), in contrast to our paleoclimate data. Long and well-validated proxy reconstructions and some state-of-the-art general circulation models therefore disagree about the sign of the hydroclimatic response of the southeast Asian monsoon to explosive volcanism. This disagreement is observed irrespective of the event lists considered here, and does not appear to be a consequence of the method. This pattern is further enhanced if recent eruptions corresponding to El Niño events in 1963 and 1982 are not included in the SEA (see Figure S3 of the auxiliary material). Indeed the widest rings in our *Fokienia hodginsii* chronology correspond to years of known, larger-magnitude Medieval volcanic eruptions [*Buckley et al.*, 2010]. This inconsistency suggests problems with one or both of the model and data sets.

[11] While both the BDNP and MADA paleoclimate data are validated against instrumental drought records, it might be possible that wider rings following volcanic eruptions could partially reflect a transient response to diffuse light conditions [cf. *Robock*, 2005]. However, comparisons of the modeled monsoon response to the MADA (Figures 2 and 3) indicate that the simulated and observed anomaly sign is likewise opposite over central Asia, and which would be inconsistent with an overall control by diffuse light. More importantly, the BDNP chronology reproduces the known (El Niño) dry conditions in southeast Asia following the eruptions of El Chichon and Pinatubo [*Trenberth and Dai*, 2007; *Buckley et al.*, 2010]. The proxy data therefore almost certainly continues to reflect local moisture conditions even in eruption years.

[12] Another possible source for the discrepancy between models and data is the simulated response of monsoon cir-

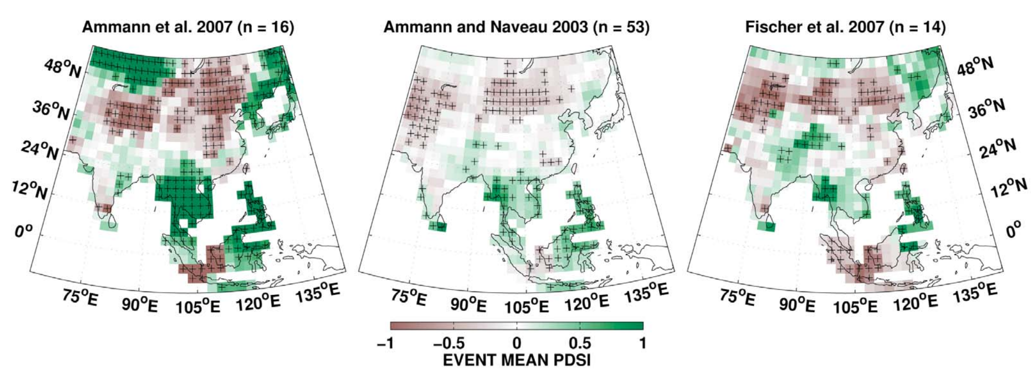


**Figure 2.** Superposed epoch analysis using the reconstructed PDSI values from the Monsoon Asia Drought Atlas (MADA) [*Cook et al.*, 2010] and the sets of events years shown in Table 1. Statistically significant (90% one-tailed) epochal anomalies based on Monte Carlo resampling (n = 10,000) are indicated by crosses.

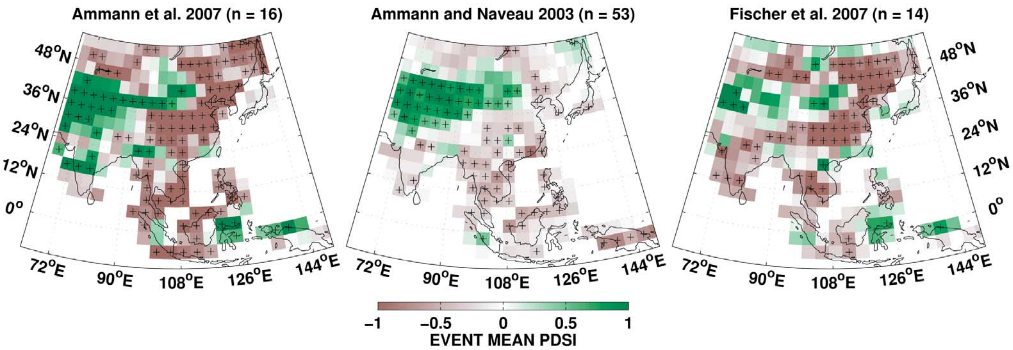


**Figure 3.** As in Figure 2, but using PDSI values derived from the millennium forced simulation of the NCAR CSM 1.4 [*Ammann et al.*, 2007].

culation to short-term radiative cooling due to volcanic aerosols. In their sensitivity modeling of the tropical response of the CCSM3 to large volcanic eruptions, *Schneider et al.* [2009] interpreted the simulated reduction of southeast Asian summer monsoon precipitation to reflect the direct influence of the reduction in shortwave radiation due to aerosol forcing and the enhanced cooling in the low latitudes of the summer hemisphere relative to the winter hemisphere. The paleoclimate data from southeast Asia suggest that in eruption years the direct effect is offset or overwhelmed by indirect or dynamical influences.

[13] Indeed, the modeled and observed [*D'Arrigo et al.*, 2008] tropical SST cooling following tropical volcanic eruptions might suggest a La Niña type influence on the Asian monsoon, although there is some discrepancy between the findings of *Adams et al.* [2003] and *D'Arrigo et al.* [2008] concerning the possible response of the ENSO system to volcanism. And while the observations from 1991–1992 CE by *Trenberth and Dai* [2007] match expectations from model simulations following explosive volcanism, the observed precipitation anomalies in southeast Asia and elsewhere for those years are also consistent with El Niño anomalies. All three event lists do suggest somewhat drier but mostly non-significant conditions in mainland southeast Asia in the years following eruptions (Figure 1). While this may simply reflect the biennial behavior of the monsoon or the dominant periodicity of the ENSO system, it could also reflect the tendency for El Niño events to follow tropical eruptions [*Adams et al.*, 2003] or the phase-locking of the ENSO and monsoon systems in response to periods of increased volcanism, as hypothesized by *Maraun and Kurths* [2005].

[14] It is possible that other important but distal influences on the monsoon may not be completely represented in climate models. For instance, climate in the North Atlantic is known to both respond to volcanic forcing and potentially influence the strength of the Asian monsoon. Models from the AR4 ensemble tend to underestimate the Northern Hemisphere warming due to volcanic eruptions and the annular mode response is too weak compared to observations [*Miller et al.*, 2006; *Stenchikovet al.*, 2006], although *Schneider et al.* [2009] suggest that radiative effects of large eruptions like that in 1258 CE could overwhelm dynamical effects. Some models may also have difficulty with simulating the true response of the ENSO system to radiative forcing [*Collins and the CMIP Modeling Groups*, 2005], which might further confound the ability of GCMs to completely reproduce the balance of radiative and dynamical influences on the monsoon.

## 5. Conclusion

[15] The models examined here and the paleoclimate data disagree on the sign of the climate response over the Asian monsoon region to radiative forcing due to explosive volcanism. Well-validated proxy reconstructions of drought indicate that the observed pattern, particularly prior to the late 20th century, is an anomalously wet southeast Asia and dry conditions over central Asia. That CSM1.4 [this study and *Fan et al.* 2009], CCSM3 [*Schneider et al.*, 2009], and GISS ModelE [*Oman et al.*, 2005] all suggest nearly opposite signed event year anomalies in these regions compared to the paleoclimate data could suggest that some GCMs do not correctly capture the balance of important coupled ocean-atmosphere processes involved in the response of Asian climate to radiative forcing. This disagreement, however, may provide important and useful clues toward further refinement of the next generation of climate models.

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C. M. Ammann, Climate and Global Dynamics Division, National Center for Atmospheric Research, 1850 Table Mesa Dr. Boulder, CO 80307-3000, USA.

K. J. Anchukaitis, B. M. Buckley, E. R. Cook, and R. D. D'Arrigo, Lamont-Doherty Earth Observatory, The Earth Institute at Columbia University, 61 Route 9W, Palisades, NY 10946, USA. (kja@ldeo.columbia.edu)

B. I. Cook, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA.